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Synthesis of Unequally Spaced Antenna Array by Using Inheritance Learning Particle Swarm Optimization

V.N.S. Sheshma Kumari

Abstract: In this paper, synthesis of unequally spaced linear antenna arrays based on an inheritance learning particle swarm optimization (ILPSO) is presented. In order to improve the optimization efficiency of the PSO algorithm, we propose an inheritance learning strategy that can be applied to different topology of different PSO algorithms. In ILPSO algorithm, each cycle contains several PSO optimization processes, and uniform initial particle positions, part of which inherited from the good results in pre-cycles, are adopted in post-cycles ILPSO enhances the exploration ability of PSO algorithm significantly, and can escape from the trap of local optimum areas with greater probability. The results demonstrate good performance of the ILPSO in solving a set of eight 30-D benchmark functions when compared to nine other variants of the PSO. The novel proposed algorithm has been applied to different element , position-only array synthesis. Simulation results show that ILPSO obtains better synthesis results reliably and efficiently.

Keywords: ILPSO algorithm, PSO algorithm, PSO Optimization, 30-D benchmark functions

1. Introduction

"Antennas are metallic structures designed for radiating and receiving electromagnetic energy". An antenna acts as a transitional structure between the guiding device (e.g. waveguide, transmission line) and the free space. According to IEEE, an antenna is a "transmitting or receiving system that is designed to radiate or receive electromagnetic waves with extensive applications in all communication, Radar and in Bio-Medical systems"

An antenna is basically a transducer. It converts radio frequency (RF) electrical current into an electromagnetic (EM) wave of same frequency. It produces electric and magnetic fields, which constitute an electromagnetic field.

The transmission and reception of EM energy is obtained by this field. It forms a part of transmitter as well as receiver circuits. Its equivalent circuit is characterized by the presence of distributed elements, namely, resistance, inductance, and capacitance. The current produces a magnetic field and a charge produces an electrostatic field.

When RF signal is applied to an antenna, electric and magnetic fields are produced. These two fields constitute the EM wave. As a result, antenna is known as a generator/radiator of EM waves and it is also a sensor of EM waves.

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1.1 Radiation from an Antenna

A conducting wire radiates mainly because of time-varying current or an acceleration (or deceleration) of charge. If there is no motion of charges in a wire, no radiation takes place, since no flow of current occurs. Radiation will not occur even if charges are moving with uniform velocity along a straight wire. However, charges moving with uniform velocity along a curved or bent wire will produce radiation. If the charge is oscillating with time, then radiation occurs even along a straight wire. The radiation from an antenna can be explained with the help of Figure 1.1 which shows a voltage source connected to a two conductor transmission line.

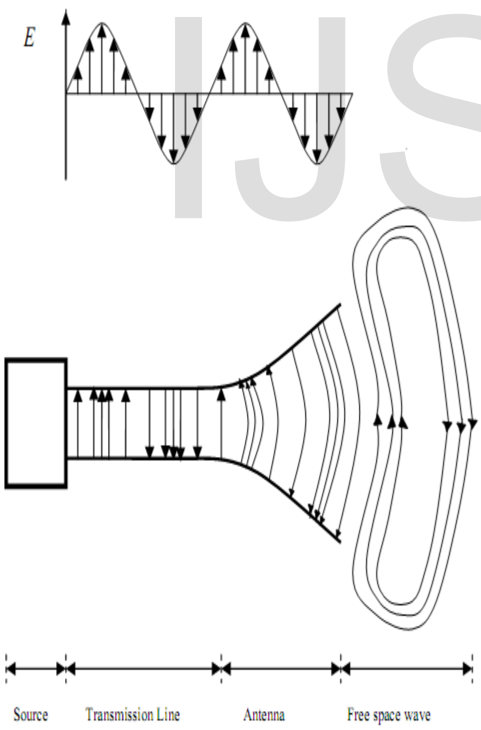

Figure 1.1: Radiation from an antenna

When a sinusoidal voltage is applied across the transmission line, an electric field is created which is sinusoidal in nature and this result in the creation of electric lines of force which are tangential to the electric field. The magnitude of the electric field is indicated by the bunching of the electric lines of force. The free electrons on the conductors are forcibly displaced by the electric lines of force and the movement of these charges causes the flow of current which in turn leads to the creation of a magnetic field.

1.2 Antenna Parameters

1.2.1 Antenna Impedance, Z_a : It is defined as the ratio of input voltage to input current.

$$Z_a = \frac{V_i}{I_i}\Omega$$

Z_a is a complex quantity and it is written as

$Z_a = R_a + j X_a$

Here, the reactive part X_a results from fields surrounding the antenna. The resistive part, $R_a = R_l + R_r$ where R_l represents losses in the antenna. R_r represents radiation resistance.

1.2.2. Radiation Resistance R_r : is defined as a fictitious or hypothetical resistance that would dissipate an amount of power equal to the radiated power.

$$\mathbf{R_r} = \frac{Powerradiated}{I_{rms}^2}$$

1.2.3. Directional Characteristics: These are also called radiation characteristics or radiation pattern. These are of two types:

1. Field Strength pattern it is the variation of the field strength as a function of θ .

2 .Power pattern it is the variation of radiated power with θ . P vs. θ is called Power pattern.

1.2.4. Radiation pattern: It is a three dimensional variation of the radiation field. It is a pattern drawn as a function θ and ϕ . The pattern consists of one main lobe and a number of minor or side lobes. An isotropic antenna is one which radiates equally in all directions. If the total power radiated by the

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isotropic antenna is *P,* then the power is spread over a sphere of radius *r; so* that the power density *S* at this distance in any direction is given as:

$$S = \frac{P}{Area} = \frac{P}{4\pi r^2}$$

Then the radiation intensity for this isotropic antenna U_i can be written as:

$$U_i = S\ r^2 = \frac{P}{4\pi}$$

An isotropic antenna is not possible to realize in practice and is useful only for comparison purposes. A more practical type is the directional antenna which radiates more power in some directions and less power in other directions. A special case of the directional antenna is the Omni directional antenna whose radiation pattern may be constant in one plane (e.g. E-plane) , varies in an orthogonal plane (e.g. H-plane). The radiation pattern plot of a generic directional antenna is shown in Figure 1.2.

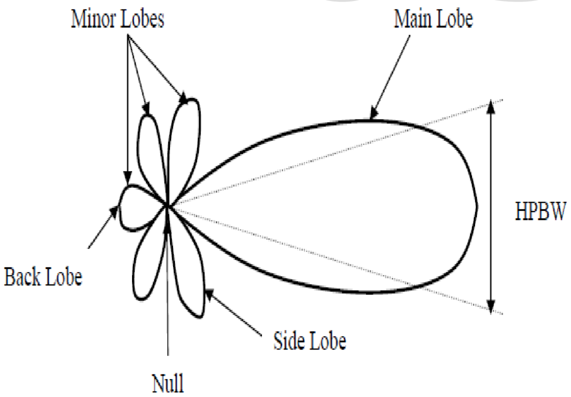

Figure 1.2: Radiation pattern of a generic Omni directional antenna

1.2.5. Lobes

Any given antenna pattern has portions of the pattern that are called lobes. A "lobe" can be a main lobe, a side lobe or a back lobe and these descriptions refer to that portion of the pattern in which the lobe appears. In general, a *lobe* is any part of the pattern that is surrounded by regions of relatively weaker radiation. So a lobe is any part of the pattern that "sticks out" and the names of the various types of lobes are somewhat self-explanatory. Figure1.3 provides a view of a radiation pattern with the lobes labelled in each type of plot.

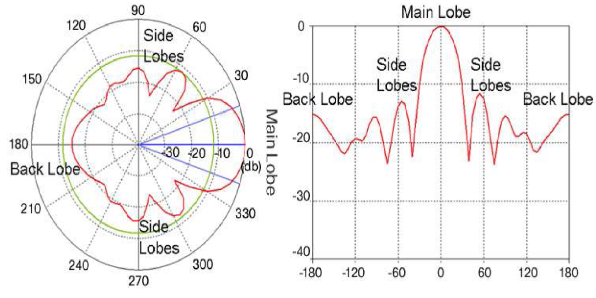

Figure 1.3: Radiation patterns in Polar and Cartesian coordinates showing various types of lobes

1.2.6. Radiation Intensity: Is defined as the power radiated in a given direction per unit solid angle.

$$RI = \frac{r^2 E^2}{\eta_0} = r^2 P \quad \text{Watts/unit solid angle.}$$

Here η_0 =Intrinsic impedance of the medium (Ω) r = radius of the sphere (meter), P= power radiated instantaneously, E= Electric Field Strength (V/m)

1.2.7. Directive gain: Is defined as the ratio of intensity of radiation in a specified direction to the average radiation intensity.

$$g_d = \frac{RI}{RI_{avg}} = \frac{RI}{\omega_r / 4\pi},$$

Where ω_r = radiated power

1.2.8. Directivity: Is defined as the ratio of maximum radiation intensity to the average radiation intensity.

$$D = (g_d)_{\max}$$

1.2.9. Power gain: Is defined as the ratio of 4π times radiation intensity to the total input power.

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$$g_p = \frac{4\pi RI}{\omega_t}$$

1.2.10. Antenna efficiency: Is defined as the ratio of radiated power to the input power.

$$\eta = \frac{\omega_r}{\omega_t} = \frac{\omega_r}{\omega_r + \omega_l}$$

1.2.11. Voltage Standing Wave Ratio (VSWR):

In order to an antenna to operate efficiently, maximum transfer of power must take place between the transmitter and the antenna. Maximum power transfer can take place only when the impedance of the antenna (Z_{in}) is matched to that of the transmitter (Z_S). According to the maximum power transfer theorem, maximum power can be transferred only if the impedance of the transmitter is a complex conjugate of the impedance of the antenna under consideration and vice-versa. Thus, the condition for matching is

$$Z_{in} = Z_S^*$$

$$Z_{in} = R_{in} + jX_{in} \qquad Z_s = R_s + jX_s$$

If the condition for matching is not satisfied, then some of the power maybe reflected back and this leads to the creation of standing waves, which can be characterized by a parameter called as the Voltage Standing Wave Ratio (VSWR).

VSWR is given by:

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|}$$

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_{in} - Z_s}{Z_{in} + Z_s}$$

Where Γ is called the reflection coefficient

V_{rs} is the amplitude of the reflected wave

Vi is the amplitude of the incident wave

The VSWR is basically a measure of the impedance mismatch between the transmitters and the antenna. The higher the VSWR, the greater is the mismatch. The minimum VSWR which corresponds to a perfect match is unity. A practical antenna design should have an input impedance of either 50 Ω or 75 Ω since most radio equipment is built for this impedance.

1.2.12. Return Loss (R_L): The Return Loss (R_L) is a parameter which indicates the amount of power that is "lost" in the load and does not return as a reflection. As explained in the preceding section, waves are reflected leading to the formation of standing waves, when the transmitter and antenna impedance do not match. Hence the R_L is a parameter similar to the VSWR to indicate how well the matching between the transmitter and antenna has taken place. The R_L is given as

$$R_L = -20 \log_{10}|\Gamma|$$

1.2.13. Polarization

Polarization of a radiated wave is defined as "that property of an electromagnetic wave describing the time varying direction and relative magnitude of the electric field vector". The polarization of an antenna refers to the polarization of the electric field vector of the radiated wave

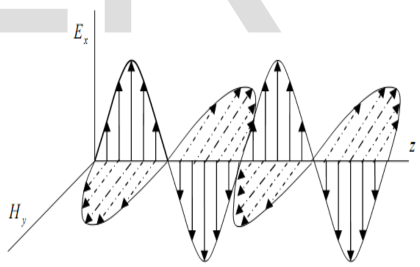

Figure 1.3: A linearly (vertically) polarized wave

1.2.14. Bandwidth

The bandwidth of an antenna is defined as "the range of usable frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard." The bandwidth can be the range of frequencies on either side of the center frequency where the antenna characteristics like input impedance, radiation pattern, beam width, polarization, side lobe level or gain, are close to those values which have been obtained at the center frequency.

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$$BW_{narrowband}(\%) = \left[\frac{f_H - f_L}{f_C}\right]100$$

where f_H = upper frequency, f_L = lower frequency, f_C = center frequency

2. Design of an Antenna Array

Basically, **Fourier Transform** of f(x) is defined as

$$F(\omega) \equiv \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(x)\, e^{-j\omega x}\, dx$$

and Inverse **Fourier Transform** of F(ω) is defined

$$F(\omega) \equiv f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(\omega)\, e^{j\omega x}\, d\omega$$

Like F(ω) and f(x) are related, Fourier Transform pair can be used to relate far-field and amplitude distribution of the array.

As a result, this method is used to design the excitation distribution of either a continuous line source or a discrete array for a specified radiation pattern.

2.1 Line source design by Fourier Transform method

Line source is defined as a continuous distribution of current along a line segment.

Let L be the length of the line source. Then the normalized space factor is given by

$$E(\phi) = \int_{-L/2}^{L/2} A(x) e^{j(K\sin\phi + \alpha_e)x} dx$$

$$= \int_{-L/2}^{L/2} A(x) e^{jyx} dx$$

$$y = K \sin \varphi + \alpha_e$$

(or)

$$\phi = \sin^{-1}\left(\frac{y - \alpha_e}{K}\right)$$

α_e = Excitation phase

A(x) = Desired amplitude distribution

E(φ) = Desired radiation pattern

Although the amplitude distribution extends from –L/2 to L/2 only, the limits can be extended to infinity in (4.9). Hence, using the concept of Fourier Transform, the field expression is written as

$$E(\phi) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(x) e^{jyx} dx$$

Therefore, its corresponding Transform pair is given by

$$A(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E(y) e^{-jxy} dy$$

or

$$A(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E(\phi) e^{-jxy} dy$$

Here E(φ) represents specified radiation pattern and A(x) is the required amplitude distribution. For a line source, the normalized amplitude distribution is given by

$$A(x) = \int_{-\infty}^{\infty} E(\phi) e^{-jxy} dy \qquad \text{for} -L/2 \le x \ge L/2$$

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= 0 else where

Let the desired pattern array factor of a linear array be given by

$$E(\phi) = E(y) = \sum_{m=-n}^{n} A_m(x) e^{jmy}$$

Here, $y = Kd \sin \varphi + \alpha_e$

$A_m(x)$ = Excitation coefficient

N = 2n + 1 = No. of elements

d = spacing between the elements

The location of elements for odd no. of elements are given by

$X_m = md$, m = 0, ±1, ±2, ………..,±n

The normalized excitation coefficients or levels of the array are obtained by Fourier formula:

$$A_m(x) = \int_{-\pi/2}^{\pi/2} E(\phi)\, e^{-jmy} dy$$

, $-n \le m \le n$

When the number of elements are even (N = 2n), the desired field pattern is given by

$$E(\phi) = E(y) = \sum_{m=-n}^{-1} A_m(x) e^{j[(2m+1)/2]y} + \sum_{m=+1}^{n} A_m(x) e^{j[(2m-1)/2]y}$$

The locations of the elements are at

$$x_m = \left(\frac{2m-1}{2}\right)d, \quad 1 \le m \le n$$

$$x_m = \left(\frac{2m+1}{2}\right)d, \quad -n \le m \le -1$$

The normalized excitation coefficients of the array are again obtained by the Fourier formula given by

$$A_m(x) = \int_{-\pi/2}^{\pi/2} E(\phi)\, e^{-j[(2m+1)/2]y} dy \quad , -n \le m \le -1$$

$$A_m(x) = \int_{-\pi/2}^{\pi/2} E(\phi)\, e^{-j[(2m-1)/2]y} dy \quad , 1 \le m \le n$$

$$A_m(x) = \int_{-\pi/2}^{\pi/2} E(\phi) e^{-jmy} dy, \quad -n \le m \le n$$

d = $\frac{\lambda}{2}$ is usual spacing in many applications.

If d < $\frac{\lambda}{2}$, super directive arrays result which are undesirable and impractical.

If d > $\frac{\lambda}{2}$, the patterns contain grating lobes which are again undesirable.

The patterns for microstrip antenna array are calculated by

$$E_a(\phi) = E(\phi) \times E(y)$$

Where

$$E(\phi) = \frac{\sin\left(\frac{k_0 h}{2}\cos\phi\right)}{\frac{k_0 h}{2}\cos\phi} \sin\left(\frac{k_0 L}{2}\cos\phi\right)$$

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$$E(y) = \sum_{m=-n}^{-1} A_m(x)\, e^{j[(2m+1)/2]y} + \sum_{m=+1}^{n} A_m(x)\, e^{j[(2m-1)/2]y}$$

$$x_m = \left(\frac{2m-1}{2}\right)d, \quad 1 \le m \le n$$

$$x_m = \left(\frac{2m+1}{2}\right)d, \quad -n \le m \le -1$$

$y = K \sin \varphi + \alpha_e$

α_e = Excitation phase

$A_m(x)$ = Desired amplitude distribution

$k = 2\pi/\lambda_0$

3. Particle SWARM Optimization

Particle swarm optimization(PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. It solves a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle's movement is influenced by its local best known position but, is also guided toward the best known positions in the search-space, which are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions.

4.Inheritance Learning PSO:

Though we can improve LDWPSO performance and success probability by suitable use of LDWPSO, the precision problem still exists higher than 500. The suitable maximal generation strategy improves the balance searching ability and the success probability of LDWPSO, but the solution precision is still not satisfying.

In order to keep a balance of searching ability and improve the results precision, the inheritance learning PSO (ILPSO) is presented. The ILPSO can serve as a frame or a container for single PSO optimization processes. ILPSO works with process cycles, each of which is consist of a number of single PSO optimizing processes. Each single PSO optimizing process uses the same parameter set, such as w, c 1 , c 2 , population size and maximal generation. The maximal generation is suitable for better balance searching ability.

In an ILPSO cycle, a number of single PSO process are executed independently. This strategy helps ILPSO to escape from the trap of local optimum area with greater probability. Processes in one cycle (except the first cycle) using uniform initial particle position which inherited from previous cycle. ILPSO works with tremendous balance searching abilities and swarm diversities, which improves algorithm performance greatly in a simple way, especially on complex multidimensional problems with a very large maximal generation.

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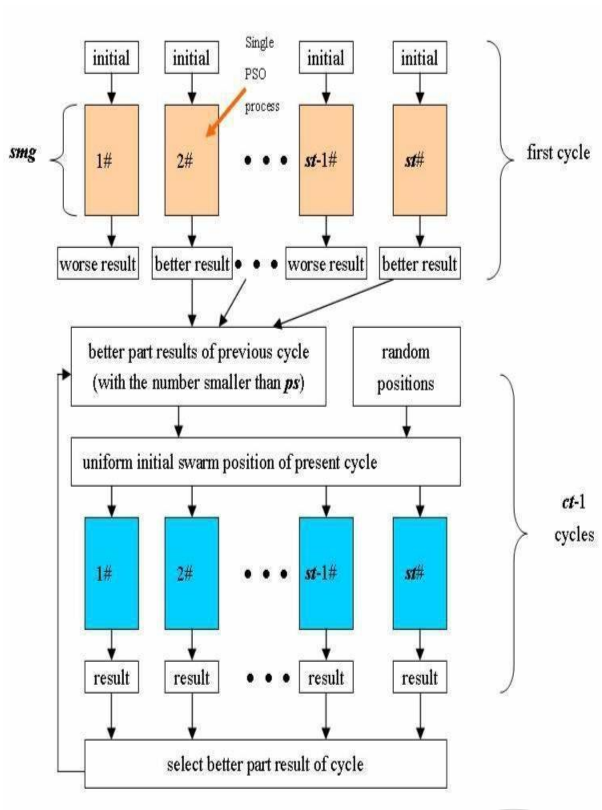

Figure 4.1 Algorithm frame of ILPSO

4.1 Simulation of ILPSO Algorithm

To verify its effectiveness, ILPSO has been applied to classical benchmark functions. All simulations are conducted in a Windows 7 Professional OS environment using 12-core processors with Intel Xeon (R), 3.33 GHz, 72 GB RAM and the codes are implemented in Matlab 7.10.

4.2. Benchmark Functions:

Test functions are important to validate and compare the performance of optimization algorithms. There have been many test or benchmark functions reported in the literature; however, there is no standard list or set of benchmark functions. Ideally, test functions should have diverse properties so that can be truly useful to test new algorithms in an unbiased way. For this purpose, we have reviewed and compiled a rich set of 175 benchmark functions for unconstrained optimization problems with diverse properties in terms of modality, separability, and valley landscape.

This is by far the most complete set of functions so far in the literature, and tt can be expected this complete set of functions can be used for validation of new optimization in the future.

No. of Elements	FSLL by using matlab	FSLL by using ILPSO
2	-15db	-18db
4	-18db	-19db
8	-21db	-25db
16	-16db	-18db
32	-22db	-23db

Figure 4.1 First Side Lobe Level Suppression (FSLL) using ILPSO algorithm.

5. Conclusion

This paper illustrated the use of PSO algorithm in the pattern synthesis of antenna arrays. And a novel PSO algorithm named ILPSO is proposed. ILPSO can provide better global searching ability and can easily escape from the local optimum. In each cycle, for a better balance of searching ability, single PSO process works with a suitable maximal generation. The inheritance learning between cycles can strengthen the swarm diversity and keep the exploration ability. ILPSO finds the global optima in most of eight 30-D benchmark functions. It works more effectively and adaptively on different problems when compared to nine other PSO variants . ILPSO can significantly improve the PSO's performance and find the global optima on most benchmark functions whether they are

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rotated or not. In addition results of unequally spaced linear antenna array have been presented. When applied to the side lobe level suppression, ILPSO obtains the better performance. Thus ILPSO obtains better results reliably and efficiently.

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Author Profile

Nooka Sai Sheshma Kumari Vunduru received the M.Tech degree in Electronics and Communication Engineering from Andhra University in 2016.